Chapter 7
Managing Chernozem for Reducing Global Warming

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Abstract Chernozems or Black Earth in Russian (Mollisols in the USDA taxonomy), cover a total of 916 million ha or 7% of the world's ice-free land: 485 Mha in Eurasia, 290 Mha in North America and 102 Mha in South America. On the occasion of the first World Soil Day, 5th December 2005, the Chernozem was proclaimed *Soil of the Year* because of its environmental, economic and societal significance. Chernozems are formed under grassland across the Steppes of Eastern Europe, Russia and Central Asia, the Prairies in North America and on the Pampas in South America, under a wide range of climate with mean annual temperatures of 5–20 °C and annual rainfall of 500–1500 mm. Their thick, humus-rich topsoil contains 4–16% organic matter or 2–8% soil organic carbon (SOC) which creates a favourable structure, high water retention capacity and large plant nutrient reserves; and their subsoils exhibit a concentration of primary and secondary carbonates. Land misuse and soil mismanagement have accelerated soil erosion, undermined their productivity and depleted SOC with associated emissions of CO_2, CH_4 and N_2O. Fifty years or more of continual cultivation has depleted SOC down to depths of 120–130 cm with losses of 38–43% from the top 0–10 cm layer. Restoring degraded Chernozems is a win-win-win strategy with agronomic, environmental, economic and societal benefits including advancing the UN Sustainable Development Goals (SDGs). Restoration would sustain and enhance crop yields, use-efficiency of inputs and advance SDG2 (Zero Hunger). It would reduce gaseous emissions and sequester carbon while reducing risks of accelerated soil erosion and non-point-source pollution, advancing SDGs 6 (Clean Water) and 13 (Climate Action). It would improve farm income and profitability and advance SDG1 (No Poverty). And it would improve societal wellbeing and advance SDG3 (Good Health and Wellbeing). An important global benefit of restoring degraded Chernozems would be adaptation and mitigation of climate change by offsetting anthropogenic emissions; SOC sequestration with improved management can be 0.7–1.5 MgC/ha/y.

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Introduction

Chernozem or Black Earth is the common name of the soil of the Russian Steppes; in Soil Taxonomy they are called *Mollisols* (Buol et al. 2011). The Chernozem was vividly described by Dokuchaev (1883) as 'The Tsar of soils'. Together with minerals, plants and animals, Dokuchaev considered soils 'the fourth kingdom of nature' and, because of its importance in agriculture and human wellbeing, especially in Eastern Europe, 'Chernozem for soil science is comparable with the frog in physiology or calcite in mineralogy' (Shcherbakov and Vasenev 1999; Chendev et al. 2015a, b). Chernozems of Eastern Europe are of aeolian origin, formed from thick, calcareous loess (Gerasimov 1973). The black colour is due to the high concentration of soil organic matter (SOM) and *Typical Chernozem* has a SOM content of 5–6% in the surface layer.

Globally, Chernozems along with their dryland cousins the *Kastanozems* and non-calcareous *Phaeozems* cover a total of 916 million hectares (Mha) or 7% of the world's ice-free land area (Table 7.1). Of this, 485 Mha are in Eurasia, 290 Mha in North America and 102 Mha in South America (Liu et al. 2012; Montanarella et al. 2021). Thus, sustainable management of Chernozems has local, regional and global implications for our habitat, economy and society.

Environmentally, the big soil carbon pool in Chernozems has a significant role in the global carbon cycle (Mikhailova and Post 2006). It has two distinct but related components: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool is derived from decomposition of the remains of plants and animals, live biomass and microbial by-products; it makes up approximately 50% of soil organic matter (SOM) or humus which is primarily composed of carbon, hydrogen and oxygen; it has a large surface area, high charge density (both positive and negative) and is a reservoir of essential plant nutrients (N, P, K, Ca, Mg, Fe, Zn, Mo etc.). As much as 90% of the SOC pool may be located in the upper 50 cm layer; under natural conditions, Chernozems can have 500 MgC/ha; 224 MgC/ha in the top 20 cm and another 211 MgC/ha

Table 7.1 Global land area under Chernozems (adapted from Liu et al. 2012)

Country/region	Area of Chernozems (million ha)
USA	200
Canada	40
Mexico	50
Eurasia	450
South America	102
China	35
World	916 (7% of the ice-free land)

in the 20–50 cm layer (Eremin 2016). However, cultivated soils commonly lose 20–30% of their native SOC; the rate of depletion of 1.0–1.4 MgC/ha/y is exacerbated by ploughing and extractive farming methods. Ploughing accompanied by increased soil erosion can lead to 38–43% losses from the SOC pool in the top 10 cm layer and measurable losses up to 60 cm depth have been observed in a 50-year continuous fallow (Mikhailova et al. 2000).

Chernozems also have a large SIC pool at >1 m depth composed of primary or lithogenic carbonates derived from the parent material, and secondary or pedogenic carbonates derived from dissolution of CO_2 in soil air to form carbonic acid, its reaction with Ca^{2+} or Mg^{2+}, and precipitation as carbonates (Lal et al. 2000). Leaching of bicarbonates is another mechanism of SIC sequestration, especially in irrigated lands (Monger et al. 2015; Bughio et al. 2016). The SIC pool in Chernozem may range from 100 to 200 MgC/ha (Mikhailova and Post 2006). The Chernozem of the northern Caucasus region is characterized by hard carbonate nodules that vary in size, internal porosity and recrystallisation, increasing with increase with the age in the chronosequence (Khokhlova et al. 2000).

Because of their economic, social and environmental importance, Chernozems were proclaimed Soil of the Year on 5th December in 2005, on the occasion of the first World Soil Day (Altermann et al. 2005). This proclamation was aimed at enhancing awareness of the importance of soil to policy makers and the general public. In contrast to plants and animals, the multiple functions and importance of soils in general, and Chernozems in particular, to ecosystem services are not readily discernible. The sequestration of SOC is also important to advance the UN Sustainable Development Goals (Groshans et al. 2018). Therefore, the objective of this chapter is to elaborate the processes, factors and practices of SOC sequestration for sustainable management of Chernozems.

Mechanisms of Sequestration of Soil Organic Carbon in Chernozems

The general principle of SOC sequestration is to create a positive soil C budget. Thus, the inputs of biomass-C (C_I) must exceed the amount of C taken out (C_O) from the soil (Eqs. 7.1 and 7.2):

$$\text{Soil C Sequestration} = C_I > C_O \tag{7.1}$$

$$\text{Soil C Depletion} = C_O > C_I \tag{7.2}$$

where C_I or inputs of carbon come from roots, straw, compost, manure and deposition (aerial, alluvial) and C_O or outputs of carbon comprise harvest (grain, straw, animal products), decomposition, erosion and leaching.

Quantification of the site-specific inputs and outputs is essential to developing the soil C budget and identifying appropriate land use and soil/crop management practices that sequester SOC, restore soil functions and provide essential ecosystem services. Once the SOC pool is being progressively improved through adoption of recommended management practices (RMP), it is essential that the sequestered C remains in the soil and is not emitted back into the atmosphere. In other words, the mean residence time (MRT) of SOC must be prolonged to the centennial and millennial-scale.

The principal determinants and control of MRT, or the mean rate of carbon renewal, are soil characteristics that: (i) enhance formation and stabilisation of micro-aggregates, (ii) reduce soil erodibility and decrease risks of accelerated soil erosion, (iii) increase translocation of SOC deep into the subsoil, (iv) moderate soil temperature and moisture regimes that affect decomposition and (v) maintain air-filled porosity at about half of the total porosity to moderate methanogenesis, nitrification and denitrification. Larionova et al. (2008) determined the rates of SOC sequestration by using natural ^{13}C abundance in Chernozem (in a 40-year corn monoculture with residue retention) and in a Grey Forest Soil. The MRT in Chernozem reached 1271–1498 years compared with 19–63 years in the Grey Forest Soil. Furthermore, the rate of renewal in Chernozem was 697 years in the upper horizons compared with 2742 years in the 40–60 cm layer and increased with a decrease in particle size.

The literature indicates several concepts in accord with the principles of increasing MRT: (1) with increase in stable micro-aggregates (Kuznetsova 1998); (2) decrease in particle size (Larionova et al. 2008); (3) increase in clay content (Bezuglova and Yudina 2006); (4) increase in input of root residues which decompose slower than the above-ground residues (Lazarev and Maisyamova 2006); and (5) with increase in the fossil humus content. In general, MRT is longer in closed (that is to say, natural) ecosystems (Ivanov et al. 2009). Herein lies the basis of sustainable management—or the principles of regenerative agriculture.

Recommended Management Practices of SOC Sequestration in Chernozems

RMPs for creating a positive soil C budget and prolonging MRT involve: (1) integrating crops with trees and livestock to create complex crop rotations and diverse farming systems, (2) adopting a system-based Conservation Agriculture (CA) featuring no-till (Lal 2015) and (3) using systems of integrated nutrient management that focus on CNPK rather than on NPK. A systems-based CA has four basic components: (i) elimination of mechanical seedbed preparation (tillage), (ii) retention of crop residues or mulch on the soil surface, (iii) use of complex crop rotations including incorporation of a cover crop in the cycle and (iv) adoption of integrated nutrient management systems with a judicious combination of organic and synthetic materials and discriminate use of supplementary chemical fertilizers based on soil

testing and the desired crop yield. On the basis of data from long-term soil management experiments on some Canadian Chernozems (Dumanski et al. 1998; Bremer et al. 2008; Zavalin et al. 2018), the following RMPs are proposed: (i) elimination or reduction of summer fallow, (ii) conversion of fallow to hay or cereals, (iii) balanced application of plant nutrients, (iv) adoption of effective measures for soil and water conservation and (v) use direct seeding methods. In the case of Canada, adoption of these RMPs could sequester 50–75% of total agricultural emissions of CO_2 for the 30-year period from 1998 to 2028 (Dumanski et al. 1998; Zavalin et al. 2018).

Protection/Restoration of Chernozems in Eastern Europe and the US Great Plains

In Eastern Europe, extractive farming and unsustainable management of the Chernozems reduced their productivity and severely depleted of their SOC pool by the mid-nineteenth century. Accelerated erosion by wind and water was the principal cause (Chendev et al. 2015a, b). A program to restore degraded Chernozems, generally known as Stalin's Plan for the Transformation of Nature, was approved in October, 1948. It involved establishing windbreaks and constructing ponds to increase water storage on about 120 Mha of degraded Chernozems, and irrigation across three major river basins, the Dnieper, Don and Volga covering a distance of 1000 km (Altermann et al. 2005). Understanding the historical evolution of soil/landscape processes and properties is pertinent to assessing the effectiveness of such a restorative program. Over time, these shelter belts enhanced build-up of SOC; similar accumulation of SOM in the 0–30 cm layer with the establishment of shelterbelts was observed on the Great Plains. Over the 55-year period since the establishment of shelterbelts in Russia, the average rate of SOC sequestration was 0.7–1.5 MgC/ha/y. In comparison, the rate of SOC sequestration in South Dakota was 1.9 MgC/ha/y (Chendev et al. 2015a, b).

SOC Dynamics in Chernozems

Formation of stable micro-aggregates protects and stabilizes SOC. The protected SOC pool encapsulated within stable micro-aggregates can be enriched in otherwise labile fractions of SOC (Rodionov et al. 2001). On the contrary, cultivation breaks down water-stable aggregates, increases mineralization of SOM, and decreases biological activity (Kuznetsova 1998; Rusanov 1998). After harvest, during the period from September to May, decomposition of stubble is more rapid than that during the summer. Further, the decomposition of root residues is slower than that of the shoot residues (Lazarev and Maisyamova 2006). Ploughing may deplete the SOC pool of Chernozems at the rate of ~1 MgC/ha/y (Eremin 2016). Ploughing and

use of chemical fertilizers can alter biological activity, and some of these changes may be irreversible (Devyatova and Shcherbakov 2006).

Managing the SOC Pool in Chernozems

Since the 1980s, there has been an increasing interest in the sustainable management of Chernozems and, specifically, the amelioration/restoration of their properties (Shcherbakov and Vasenev 1999). There are also growing concerns regarding transformation and mineralization of the SOM, severe agronomic degradation and depletion of soil fertility, and accelerated rates of erosion of Chernozems including a progressive formation of gullies and severe dissection of the landscape. With business as usual, the degradation of Chernozems may be exacerbated by climate change. Thus, restoration and sustainable management of Chernozems is an imperative. Furthermore, 23 Mha of Eurasian steppe grassland converted into cropland in northern Kazakhstan from 1954 to 1963 (the so-called Virgin Lands Scheme) and abandoned with the collapse of Soviet Union must also be restored (Kraemer et al. 2015). However, technological options to re-cultivate the abandoned croplands in Russia, Ukraine and Kazakhstan (Meyfroidt et al. 2016) should be objectively and critically evaluated.

It is widely accepted that fallow aggravates the depletion of SOC pool (Janzen 1987). Potentially mineralizable SOC in a ploughed soil may be 1.9–3.9 times lower than that in soils under natural vegetation (Semenov et al. 2008); annual inputs of plant residues in a less frequently fallowed system would enhance potentially mineralizable carbon and restore soil quality. Karbozova-Saljnikov et al. (2004) observed that potentially mineralizable SOC was inversely proportional to the frequency of fallow; frequent fallows deplete the SOC pool through accelerated mineralization.

Increasing SOC sequestration, decreasing emissions and protecting the existing C pool in Chernozems are also appropriate strategies to mitigate climate change. Semenov et al. (2008) observed that the highest soil C sink capacity may follow the following order: *Leached Chernozem* > *Dark chestnut soil* > *Chestnut soil* > *Tundra soil* > *Grey forest soil* > *Sod-podzolic soil*. Dumanski et al. (1998) observed that the greatest potential for SOC sequestration in Canada is in Chernozems. In general, conversion of conventional ploughing to no-till enhances SOC sequestration; the RMPs for SOC sequestration in Chernozems are adoption of CA in conjunction with the replacement of summer fallow by hay or cereals. These technological options have the potential to offset a large proportion of emissions from agricultural operations. SOC sequestration can also happen through self-restoration when farmland is abandoned. Kalinina et al. (2011) evaluated the SOC pool after 8, 19, 37 and 59 years of cultivation abandonment and self-restoration in Chernozems in Russia. Naturally, the vegetation was transformed towards virgin steppe and the soils towards natural Chernozems; the SOC content increased from 38.9 to 54.5 g/kg in the 0–10 cm layer; the SOC sequestration rate for the 59 years of self-restoration was 520 kg/ha/y and the SOC stocks increased to 91% of that of Chernozems under natural vegetation.

Sequestration of Soil Inorganic Carbon in Chernozems

Carbonate accumulation in Chernozems, as in other soils of dry climates has pedological and climatological significance (Lal 2019). Pedologically, understanding the carbonate profile is an important tool for paleo-environmental reconstruction. Forms of carbonate concentrations in Chernozems are related to past environmental conditions. In the northern Caucasus region, Khokhlova et al. (2001) compared the carbonate profile of Chernozems under irrigated and natural moisture regimes for soils buried under archaeological mounds of 1600–1700 to >5000 years BP. Analysis of the carbonate profile showed that climate of the region during the second half of the Holocene (>5000 years BP) changed from dry and warm to more humid and cooler in 5000–4000 BP and the present era. Recent changes in carbonate profile due to agricultural activities are shown by the migration of carbonates by leaching and accumulation driven by the increased wetness of the upper 3 m solum between 1973 and 2006 (Ovechkin and Bazykina 2011). The SIC pool is also affected by land use. Mikhailova and Post (2006) reported that, in the Kursk region of Russia, the SIC pools in the top 2 m were 107 MgC/ha for native grassland, 91 MgC/ha for the yearly-cut hay field, 242 MgC/ha for the continuously cropped field, and 196 MgC/ha for the 50-year continuous fallow. Most of the SIC pool was as carbonates and stored below 1 m depth.

Cultivation of Chernozems can also affect the rate of sequestration of SIC. A comparative study of the Mollisols of the U.S. Northern Great Plains and the Russian Chernozems (Mikhailova et al. 2009) showed that cultivation of these fertile, Ca-rich soils of temperate grassland ecosystems decreased SOC but increased the SIC pool (Table 7.2); cultivation increased the ratio of SIC:SOC pools.

Mollisols contain both lithogenic and pedogenic carbonates, and the increase in SIC upon cultivation may be due to formation of pedogenic carbonates. Further, most of the carbonate formation in Mollisols occurs below the root zone and, therefore, below the zone of most biological activity (Mikhailova and Post 2006; Cihacek et al. 2002). Formation of pedogenic carbonates in cultivated Chernozems also happened due to changes in soil moisture regime and deep drying of the subsoil (Lebedeva 2002).

Table 7.2 Increase in SIC pool at 0–1 m in Mollisols in the U.S. and of Chernozems in Russia (adapted and recalculated from Mikhailova et al. 2009)

Country	Soil series	SIC pool (MgC/ha)		Ratio of SIC:SOC pool	
		Grassland	Cultivated	Grassland	Cultivated
USA	Amor	77	80	0.54	0.74
USA	Shambo	78	105	0.67	0.93
USA	Stady	4	24	0.0067	0.175
Russia	Kursk	9	35	0.026	0.200

Management Effects on Soil Physical and Hydrological Properties of Chernozems

Cultivation-induced changes in the SOC pool can strongly modify soil physical, mechanical and hydrological properties. Indeed, SOC content and soil physical properties are inter-related. Bezuglova and Yudina (2006) reported that the SOC content is closely correlated with soil texture and, especially, with the clay content; changes in clay content under intensive agriculture, caused by erosion and illuviation, may also impact aggregation and the proportion of aggregated clay. Furthermore, cultivation transforms the bonded humus fraction into a more active (labile) form that can be rapidly mineralized. In the Central Russian province of the forest-steppe zone, Kuznetsova (2013) assessed the impacts of agro-technology, agro-economy and agro-ecology during 1964–2002 on physical properties of *Typical and Leached Chernozems*: mechanisation, increased use of mineral fertilizers and decreased inputs of organics exacerbated the problem of soil compaction and soil physical quality (Table 7.3).

Land use can also impact rheological characteristics as Khaidapova et al. found in *Typical Chernozem* in the country around Kursk (Table 7.4). Soils under oak forest are more resistant to changes in rheological properties under loading, and these differ from those under ploughland and fallow.

Soil water storage in cultivated versus uncultivated (virgin) Chernozem differs between wet and dry years (Table 7.5). Decline in soil water storage during the dry year is an indication of the aridization of cultivated Chernozems. On the contrary, the

Table 7.3 Cultivation effects on physical properties of *Typical and Leached Chernozem* for 0–30 cm depth (adapted from Kuznetsova 2013)

Parameter	Natural soil	Cultivated soil
Bulk density (Mg/m^3)	0.93–0.95	1.05–1.20
Total porosity (%)	60–65	55–60
Water-stable aggregates (%)	72–86	43–60
Infiltration rate (mm/h)	170–312	60–180
Field capacity (%)	34–38	32–35

Table 7.4 Effect of land use on rheological properties (adapted from Khaidapova et al. 2016)

Land use	Total C (%)	Swelling (%)	Specific surface area (m^2/g)	Moisture content (%)	
				At maximum swelling	At liquid limit
Oak forest	6.5	30.4	114.0	72.9	49.8
Ploughland	3.3	16.5	98.8	63.6	39.9
Long-term fallow	3.0	17.2	86.6	56.5	35.7

Table 7.5 Soil water storage (mm of water) in cultivated and virgin Chernozems to 2 m depth (adapted from Lebedeva 2004)

Moisture regime	Summer		Autumn	
	Steppe	Cultivated	Steppe	Cultivated
Dry	100	88	112	83
Wet	100	112	101	125

supply of water in spring may exceed the evapotranspiration and, thus, lead to increase in water storage (Table 7.4). Such differences in hydrological regimes can also lead to changes in the migrational form of pedogenic carbonates. Aridization of cultivated Chernozems leads to ascending moisture flows and the attendant development of a carbonate-accumulative horizon due to the formation of pedogenic carbonates. Rapid drying of Chernozems even in subsoil layers enhances formation of secondary carbonates (Lebedeva 2002).

Soil physical properties and moisture regimes are also affected by fertilizer use, tillage and crop rotation. Borontov et al. (2005) reported that application of organic and chemical fertilizers enhanced soil water uptake by sugar beet. Further, sugar beet in rotation with clover increased soil water consumption coefficient more than alternation with fallow. Water supply and productivity of sugar beet were greater with mouldboard ploughing and manuring than with reduced or zero tillage and chemical fertilizers.

Management Effects on Soil Erosion

Pulverization of soil by tillage is the primary cause of accelerated erosion of Chernozems. Bulygin (1993) reported that Chernozems in the steppe zone of Ukraine are severely eroded and black storms caused by wind erosion are common. Soil erosion is also widespread in ploughed croplands of Western Siberia; Tanasienko and Chumbaev (2010) reported that the water content in the surface layer exceeds field capacity in the late fall. During winter, an ice barrier is formed in the humus horizon and, being impermeable to snowmelt, such barriers increase runoff and aggravate erosion. However, Gusarov et al. (2018) report that adoption of effective conservation measures is leading to a decreasing trend of erosion of arable *Southern Chernozems* across the south-eastern boundary of Russia with Asia.

Conclusions and Researchable Priorities

Synthesis of the literature presented above supports the following conclusions:

- Cultivation of Chernozems can decrease SOC content of the surface layer by ~30% and the depletion of SOC can extend beyond 50 cm depth. The magnitude of depletion is exacerbated by ploughing and accelerated erosion by water and wind. Black dust storms are common in ploughland.
- Cultivation also degrades physical, rheological and hydrological properties of Chernozems.
- Chernozems sequester atmospheric CO_2 in the form of SOC and SIC. Whereas cultivation may decrease the SOC, it increases SIC through the formation of secondary/pedogenic carbonates. Changes in soil moisture regime also enhance the formation of pedogenic carbonates.
- Protection, restoration and sustainable management of Chernozems is a high priority because of their high soil C pool and soil C sink capacity.

Researchable priorities for management of Chernozems include:

(i) Improving quantitative estimates of the ecological state of Chernozems
(ii) Understanding the temporal changes in soil quality of abandoned cultivated Chernozems
(iii) Assessing and understanding the temporal changes in soil quality, soil properties and, in particular, SOC and SIC pools when cultivated land reverts to nature
(iv) Evaluating the potential and achievable rates of SOC and SIC sequestration in Chernozems worldwide
(v) Evaluating the cause-and-effect relationship in SOC content and crop yield on degraded Chernozems.

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